Systematic Study of $M1$ Strength in the Rare-Earth Region

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A study of magnetic dipole strength in the rare-earth region and application to the $^{148-160}$Gd isotopes has been carried out. Within the Nilsson model, all two-quasiparticle $K^\pi=1^+$ configurations have been constructed and the $M1$ strength distribution has been calculated. Information on the total summed (non-energy-weighted) $M1$ strength is obtained. The distribution of orbital and spin $M1$ strength over different energy regions and over the whole rare-earth mass region was studied. Relations to quadrupole ground-state deformation are pointed out.

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The study of magnetic properties has been one of the major topics of the nuclear shell model and still provides various surprising phenomena. These new aspects are mainly related to the fact that the collective aspects of the nuclear wave function, through the contribution to the orbital component, can be strongly excited. Single-particle aspects can more easily be detected through the intrinsic spin contributions and via one-nucleon transfer reactions.

The recent observation by inelastic electron scattering of low-lying 1^+ states carrying quite large $M1$ strength of mainly orbital character in ^{156}Gd (Ref. 1) started detailed investigations of this new $M1$ mode. It was originally interpreted as a so-called "scissor mode," which was predicted by Lo Iudice and Palumbo in their two-rotor model (TRM).[2] Here, protons and neutrons constitute deformed axially symmetric rigid bodies with symmetry axis displaced over a certain angle and performing out-of-phase rotational oscillations. An analogous picture was obtained by Faessler and Nojarov starting from the generalized Bohr-Mottelson model.[3]

Another quite successful approach is given within the proton-neutron interacting-boson model (IBM-2) in which valence nucleons are treated in pairs as s ($l=0$) and d ($l=2$) bosons.[4] Taking the charge degree of freedom into account, one can then construct states which are nonsymmetric under interchange of proton and neutron bosons. The so-called "mixed-symmetry" states can thus be obtained. This model, via its geometric analog, is very similar to the TRM, but now only valence nucleons contribute to the motion.

Since numerous new measurements have been performed using (e,e'), (p,p'), and (γ,γ') reactions, the low-lying 1^+ excitations are known throughout the nuclear mass region ranging from ^{46}Ti to ^{238}U.[5] By comparing (e,e') and (p,p') studies, information on the relative orbital to spin $M1$ component could be obtained. High-resolution (γ,γ') experiments indicated rather important fragmentation of the original 1^+ mode. In order to reproduce the fragmentation, one has to turn to microscopic approaches such as standard shell-model calculations for light nuclei near doubly closed shells[6] and random-phase-approximation and quasirandom-phase-approximation calculations for heavier, deformed nuclei. For several rare-earth nuclei, such calculations[7] have been done, but the conclusions drawn in different papers differ considerably: They depend strongly on the description of the mean field, on the way pairing correlations are included, and on the choice of the residual interactions.

Since it turns out to be quite impossible to reproduce the details of the observed $M1$ strength distribution, we study the unperturbed intrinsic two-quasiparticle picture and the related $M1$ strength. In this way, we are able to map out the variation of the total $M1$ strength over large mass regions (the rare-earth nuclei) and even obtain some information on the relative importance of orbital versus spin $M1$ contributions depending on the excitation energy and the mass number A. Moreover, the results point towards a relation between the variation of orbital $M1$ strength and the nuclear ground-state quadrupole deformation.

One of the most successful and transparent approaches to nuclear deformation and single-particle motion in deformed nuclei is the Nilsson model.[8] Using the most simple parametrization, as described in Ref. 9, the quadrupole deformed field is characterized by one parameter ϵ_2. Also taking into account the short-range pairing correlations among identical nucleons in the single-particle deformed field, the elementary modes become the one-quasiparticle excitations. Here, a constant pairing force was used, following again the prescriptions of Ref. 9.

Since our main interest centers around $M1$ properties in rare-earth nuclei, we construct all $K^\pi=1^+$ intrinsic excitations using two-quasiparticle (2qp) product states. Thus, we set up the basis

$$\{|K^\pi=1^+(i)\rangle_\pi \otimes |\tilde{0}\rangle_\nu,\ |\tilde{0}\rangle_\pi \otimes |K^\pi=1^+(j)\rangle_\nu\}\,, \qquad (1)$$

where

$$|K^\pi=1^+(i)\rangle_\rho = \alpha^\dagger_{N_i\Omega_i,\rho}\alpha^\dagger_{N_i'\Omega_i',\rho}|\tilde{0}\rangle_\rho\,, \qquad (2)$$

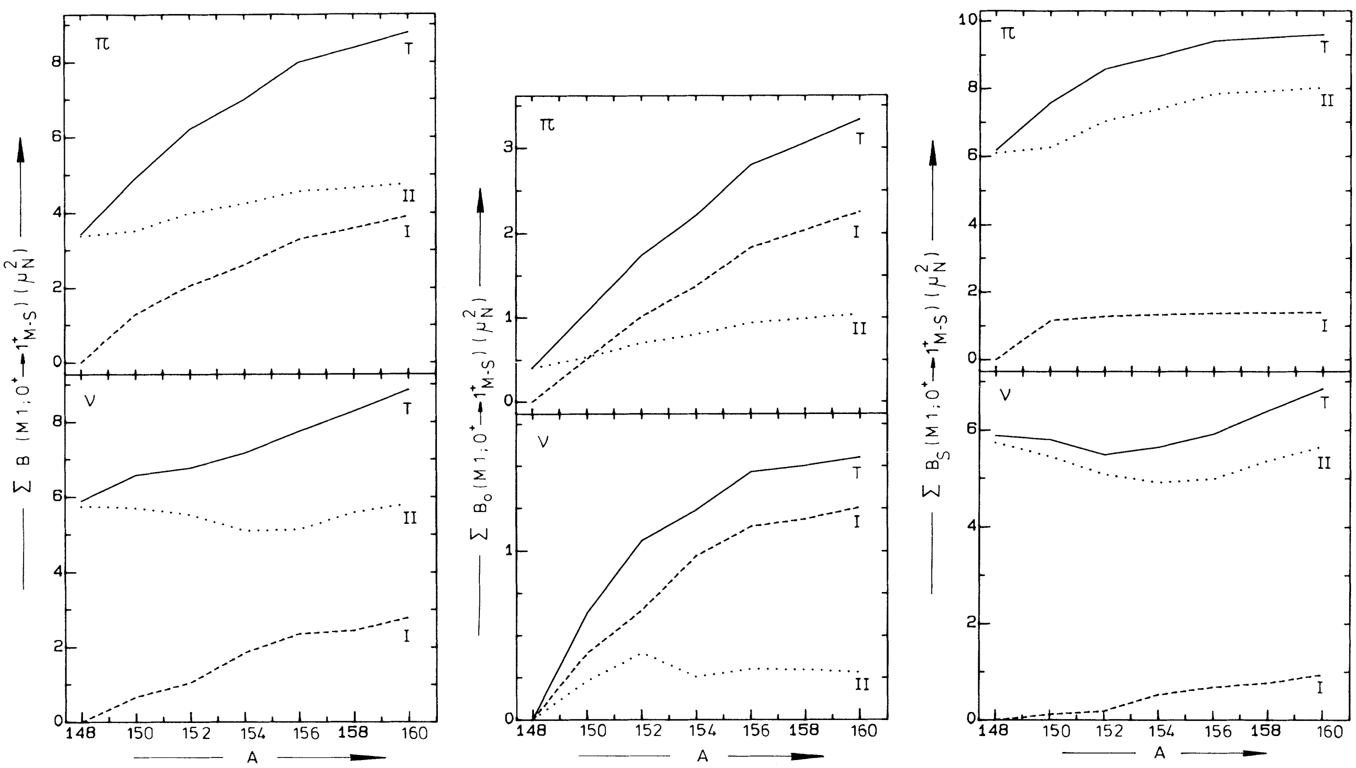

FIG. 1. The summed $M1$ strength (above for proton states, below for neutron states) for the series of Gd isotopes, over different energy regions: dashed line, region I ($E_x \leq 4$ MeV); dotted line, region II (4 MeV $< E_x \leq 9$ MeV); solid line, total amount of strength. Left panels, the total $B(M1)$ values; middle, the orbital parts; and right, the spin parts.

$\rho=\pi,\nu$, with the conditions

$$(-1)^{N_i+N_i'}=+1\,, \quad \Omega_i+\Omega_i'=1 \text{ or } |\Omega_i-\Omega_i'|=1\,. \tag{3}$$

Starting from the above basis of 1^+ 2qp configurations, we calculate the $M1$ reduced transition probabilities using the unified rotational model (with axial symmetry).[10] The following $M1$ reduced matrix element results:

$$\langle K^\pi=1^+(i)\|\hat{T}(M1)\|K^\pi=0^+\rangle$$
$$=(3/4\pi)^{1/2}(u_iv_i'-u_i'v_i)\delta_{N_iN_i'}(-1)^{\Omega_i'+1/2}$$
$$\times\sum_{l_i,\Lambda_i,\Sigma_i}\sum_{l_i',\Lambda_i',\Sigma_i'} c_{l_i\Lambda_i\Sigma_i}^{N_i\Omega_i} c_{l_i\Lambda_i\Sigma_i'}^{N_i'\Omega_i'}\delta_{l_il_i'}\{g_l[(l_i'+\Lambda_i')(l_i'-\Lambda_i'+1)]^{1/2}\delta_{\Sigma_i,-\Sigma_i'}\delta_{\Lambda_i,-\Lambda_i'+1}+g_s\delta_{\Lambda_i,-\Lambda_i'}\delta_{\Sigma_i,-\Sigma_i'+1}\}\,. \tag{4}$$

The gyromagnetic factors are taken as $g_l=g_l$(free) and $g_s=0.7g_s$(free), which seems to give an overall good agreement throughout the whole nuclear mass region.[11] We have corrected for the spurious components in the wave functions, corresponding to a rotation of the nucleus as a whole, by orthogonalizing the total $K^\pi=1^+$ basis with respect to the normalized state $\mathcal{N}\hat{J}_+|\tilde{0}\rangle$. Finally, we stress that the calculations of the unperturbed $M1$ strength distributions are performed at the equilibrium quadrupole deformation ϵ_2 as listed in Ref. 12.

We have studied the whole rare-earth region from the Ce to the Pt nuclei, thereby covering the whole $82 \leq N \leq 126$ neutron shell. Before discussing the general aspects over many nuclei, we briefly discuss the series of $^{148-160}$Gd isotopes.[13]

The magnetic dipole strength is concentrated in a relatively small energy region; still, the unperturbed $M1$ strength is appreciably fragmented for neutron as well as for proton configurations. This is mainly due to the relatively high density of 2qp states. More than 95% of the total $M1$ strength appears in transitions to $K^\pi=1^+$ states below $E_x=9$ MeV. One can, moreover, distinguish two main groups: region I with $E_x \leq 4$ MeV and region II with 4 MeV $< E_x \leq 9$ MeV. In region I, the transitions are mainly of the type $(l,j \rightarrow l,j)$ with a dominant orbital character while in region II mainly spin-flip $M1$ transitions $(l,j=l+\frac{1}{2} \rightarrow l,j=l-\frac{1}{2})$

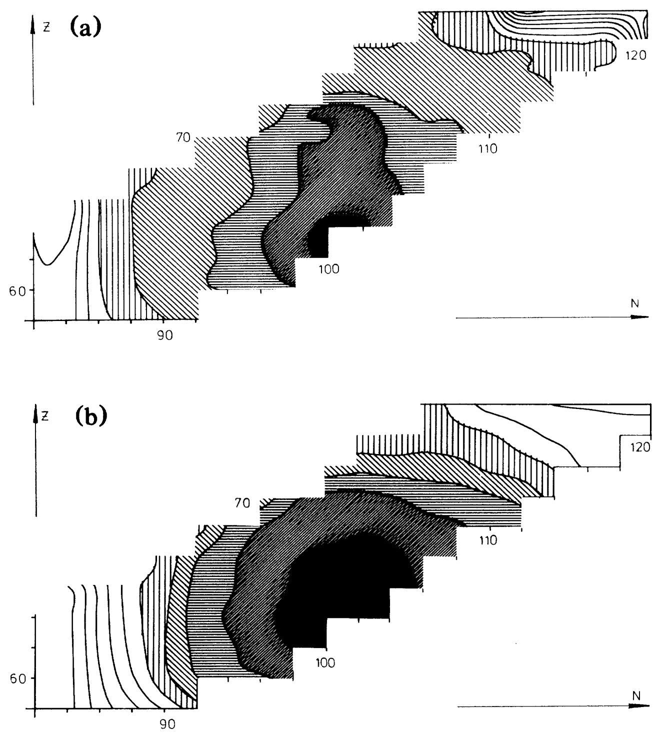

FIG. 2. Landscape patterns giving (a) the equilibrium deformation ϵ_2 and (b) the summed orbital strength for nuclei in the rare-earth region. The darkest region corresponds to the largest values; (a) from $\epsilon_2=0.27$, 0.26, 0.25 down by steps of 0.05; (b) from $\sum B_0(M1)=5\mu_N^2$ down by steps of $0.5\mu_N^2$.

occur. The concentration of orbital (spin) strength in region I (II) is very clear, as shown in Fig. 1.

A very striking feature, which is also clear from Fig. 1, is that the (mainly orbital) $M1$ strength in region I increases with increasing mass number for the Gd isotopes, or, with increasing quadrupole deformation. This particular relationship between ground-state quadrupole deformation ϵ_2 and the orbital strength throughout the rare-earth region is illustrated via the corresponding landscapes in Fig. 2. The relation between $M1$ strength and ϵ_2 deformation seems strange at first. It can, however, be understood by realizing that the orbital strength mainly originates from transitions of the type $(l,j \to l,j)$. For small deformations, a group of Nilsson orbitals having the same spherical configuration (l,j) is almost degenerate in energy. Therefore, the occupation probabilities v^2 are very similar for the whole group and this then gives rise to very small pairing factors $u_i v_i' - u_i' v_i$ in the $M1$ matrix element [see Eq. (4)]. With increasing deformation, the Nilsson orbitals separate out, thus resulting in largely different v^2 occupation probabilities, and the $M1$ transitions will become enhanced, especially for those transitions involving 1qp states near the Fermi level. This argument is illustrated in Fig. 3, for the case of ^{156}Gd. Indeed, we find that in this nucleus, the $(1h_{11/2})\frac{5}{2}^- \to (1h_{11/2})\frac{7}{2}^-$ $M1$ matrix element is large. Because of the fact that the orbitals near the Fermi level give major contributions to the total $M1$ strength, one can interpret this description as a "valence model," i.e., a microscopic counterpart of the

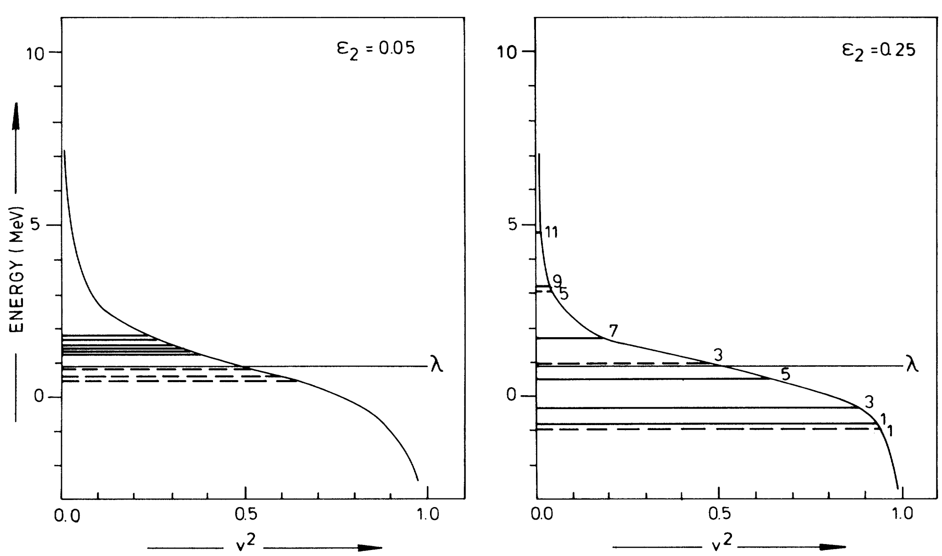

FIG. 3. Schematic picture of the influence of deformation on the $(l,j \to l,j)$ transition strength. Two groups of (l,j) Nilsson orbits are given: $1h_{11/2}$ (solid lines) and $2d_{5/2}$ (dashed lines). The length of the lines corresponding with the different levels indicates the occupation probability. The Fermi level is indicated as λ. At the right-hand side, the integer values give the double physical value of the Nilsson projection quantum number Ω of the orbit considered.

IBM-2 model. Indeed, the orbital summed $M1$ strength is very similar to what is calculated in the latter model, where in both the SU(3) and O(6) limits, the $B(M1;0^+ \rightarrow 1^+_{M-S})$ reduced transition probabilities are proportional to the product $P \equiv N_\pi N_\nu/(N_\pi + N_\nu)$, where N_π (N_ν) is the number of valence proton (neutron) particles (or holes) divided by 2.[14] It has been shown by Casten, Brenner, and Haustein that precisely this quantity P is also a measure of quadrupole deformation effects in the nuclear ground state.[15] Thereby, the increase in orbital strength in the Nilsson model and in the IBM-2 model are quite related.

As far as spin-flip transitions are concerned, it is clear that—since the appropriate Nilsson orbitals giving rise to such $M1$ transitions remain at a fairly constant energy separation as a function of deformation—the strength is much less sensitive to deformation effects.

Concluding, we point out that even though the present calculations provide the "unperturbed" $M1$ strength distribution, a general correspondence between regions with appreciable $M1$ strength is obtained. The present analyses in terms of 2qp 1^+ intrinsic excitations also point towards specific excitation energy regions where a mainly orbital (below $E_x \leq 4$ MeV) or spin-flip (near $E_x \sim 6$ MeV) character is dominant. Possible experimental evidence for such a spin-flip mode around 6–7 MeV is obtained in recent (p,p') measurements.[16] We have also indicated a very specific correlation between the overall variation in orbital $M1$ strength and the variation in ground-state quadrupole deformation in the rare-earth mass region. This relation seems to be rather general. Finally, as far as the $(l,j \rightarrow l,j)$ group of low-lying 1^+ transitions is concerned, diagonalizing the residual proton-neutron interaction can probably give rise to a more "collective" isovector orbital $0\hbar\omega$ excitation, where collectivity is to be understood as a coherent contribution of proton 2qp components, out of phase with a coherent contribution of neutron 2qp components. At present, even detailed microscopic calculations cannot give a firm conclusion about the possible existence of such a state, so that more detailed and systematic studies concerning the effects of the residual force are still worthwhile. Such work is in progress.

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